Chapter 13 - **NEUTRON AREA DETECTORS**

1. NEUTRON DETECTOR BASICS

Two-dimensional area detectors are essential components for SANS instruments. The position sensitive detection is achieved in one of two ways. (1) Delay line detectors sense the position of the detection event through the time delay at both ends of each cathode. Only two winding cathodes wires (one for X and one for Y positioning) are used. (2) The other (and most used) detection scheme uses the coincidence method whereby only X and Y events that arrive in time coincidence are counted. This last method uses 128 wires for X and 128 wires for Y cathodes and can handle higher count rates.

Most neutron area detectors use ^{3}He as the detection gas that undergoes the following nuclear reaction:

$$^{1}n_{0} + {}^{3}He_{2} \rightarrow {}^{1}H_{1} + {}^{3}H_{1} + 765\ \text{keV} \qquad (1)$$

The reaction products consist of two charged particles: a proton ($^{1}H_{1}$) and a triton ($^{3}H_{1}$) released in opposite directions with a combined kinetic energy of 765 keV. This kinetic energy is dissipated by ionization of the proportional counting gas (CF_4 mostly). Since the incident neutron kinetic energy is very small (1/40 eV for thermal neutrons), thermal neutron detectors cannot measure neutron energies; they can only detect neutron positions. The released charged particles are attracted by the anode plane high voltage and liberate electrons. These are accelerated towards the anodes and therefore create a detection cloud through secondary ionization (charge multiplication). The two cathode planes (for detection in X and Y) are located on both sides of the anode and are kept at a low bias voltage in order to increase detection behind the cathodes. The detection cloud which is created close to the anode induces a charge on the closest cathodes (through capacitive coupling) which can be sensed by the charge sensitive preamplifiers. An X-Y coincidence pair is then selected and processed as real event.

The two main suppliers of neutron area detectors are CERCA (Grenoble, France) and ORDELA (Oak Ridge, Tennessee, USA). Both types of area detectors use the coincidence method. The NIST Center for Neutron Research SANS group has experience with both detector types. A third type of area detectors uses the charge division method which is similar to the delay line method but involves measuring the produced charges on both sides of each wire. This type is not discussed.

2. NEUTRON AREA DETECTOR SPECIFICS

The $^{3}He/CF_4$ gas mixture is kept at high pressure (2.4 Bars = 243 kPa) inside the detection chamber. An additional detector "dome" chamber filled with neutron transparent ^{4}He is added in front of the detection chamber in order to equilibrate pressure on both sides of the entrance window. This helps avoid the use of thick detector entrance windows that would attenuate the scattered neutrons beam. The detector localization gap (distance between the two cathodes) is 1.5 cm and the total detection gap is 2.5 cm.

In the CERCA detector, both anode and cathode wires are made out of a CuBe alloy. Each cathode consists of a band of nine narrowly spaced stretched wires; the bands themselves are spaced 1 cm apart (center-to-center). The ORDELA detector uses one wire per cathode.

The active detection area of typical neutron area detectors is 64 cm*64 cm with a spatial resolution of either 1 cm*1 cm for the CERCA detector or 0.5 cm*0.5 cm for the ORDELA unit. The detector efficiency is high (around 75 %) for typical neutron wavelengths (around $\lambda = 6$ Å). Count rates of order $5*10^4$ counts per second over the whole detector are achieved.

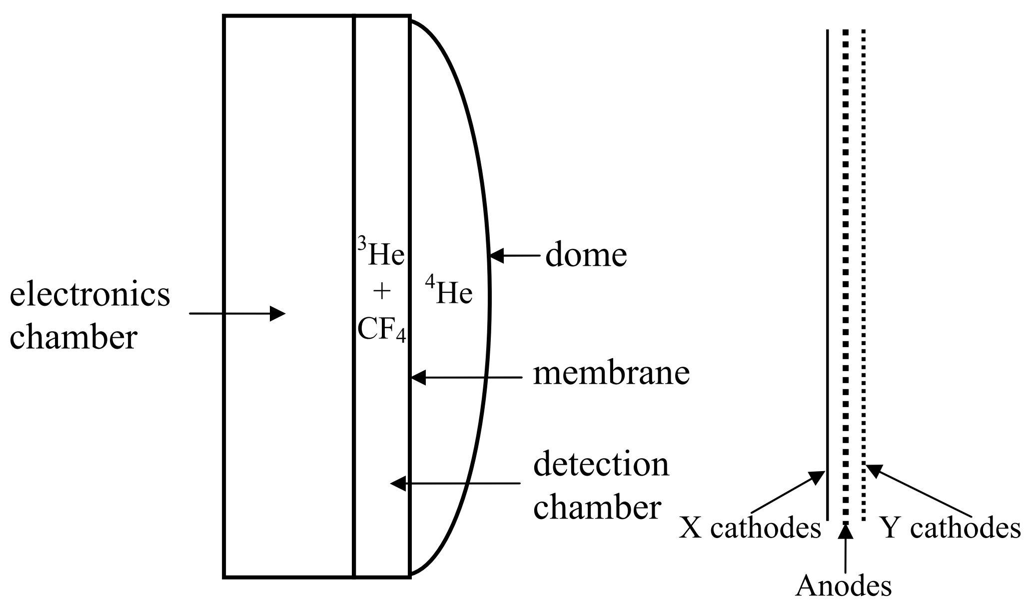

Figure 1: Schematic representation of a neutron area detector. This figure is not to scale. The detection chamber is 2.5 cm wide and 64 cm high.

Since the detector operates inside an evacuated chamber, and in order to avoid using a large number of vacuum feed-throughs for the cathode signals, all of the signal processing is performed using electronics that are mounted on the back of the detector. The detection electronics chain comprises amplification of the analog signals for each cathode wire, monitoring of X-Y coincidences and encoding to produce a digital signal which is sent out to the data acquisition system.

3. NEUTRON MEASUREMENTS

Measurements of the performance of area detectors have been conducted on both CERCA and ORDELA type detectors. Results for one or the other type are described in each of the following sections. All measurements were made using a monochromatic neutron beam.

Pulse Height Spectrum

The pulse height spectrum is measured using a multi-channel analyzer (MCA). A figure shows the pulse height spectrum of the anode plane measured on a CERCA detector at a high voltage of 2550 V. A narrow neutron peak with a resolution of about 16 % (FWHM divided by the average peak position) is observed. This main peak corresponds to the 765 keV energy released as kinetic energy during neutron capture by ^3He. That energy is split into 191 keV for the triton ^3H and 574 keV for the proton ^1H. When the detection reaction occurs close to the detector wall, one of the products (either the proton or the triton) ends up absorbed in the wall while the other one deposits its kinetic energy in the stop gas. This "wall effect" is manifested by two more peaks and the long plateau region. The triton peak can be observed at 191 keV but the proton peak has merged with the main neutron peak and cannot be resolved. The low pulse height noise is due mainly to low energy electrons that are knocked off by gamma rays that are absorbed in the detector walls. The main neutron peak at 765 keV corresponds to both proton and triton being absorbed in the detection gas.

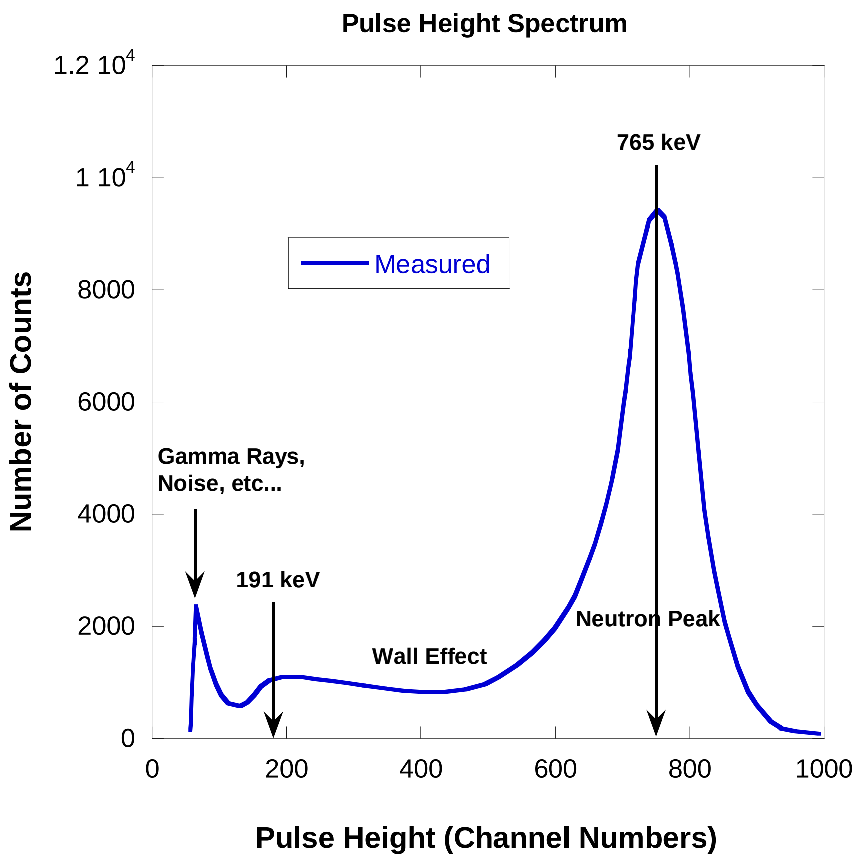

Figure 2: The anode pulse height spectrum for a CERCA detector showing a sharp neutron detection peak and low noise. The horizontal scale is in arbitrary MCA channel numbers and represents the pulse heights (measured in mV to represent the absorbed energies in keV).

Gas Multiplication Factor

Using the variation of the anode pulse height for increasing detector high voltage yields the gas multiplication curve and the gas multiplication factor which represents the number of charges produced by the detection of one neutron. A figure shows measurements made on the CERCA detector. In order to express this variation in an absolute scale, an electronics pulse equivalent to the absorption of one neutron (i.e., the creation of a charge of 0.0035 pC) is injected into the anode plane. Measuring the amplified output of this signal on the cathodes and comparing it to that output during "normal" detector operation yields a gas multiplication factor of 117 at a high voltage setting of 2700 V.

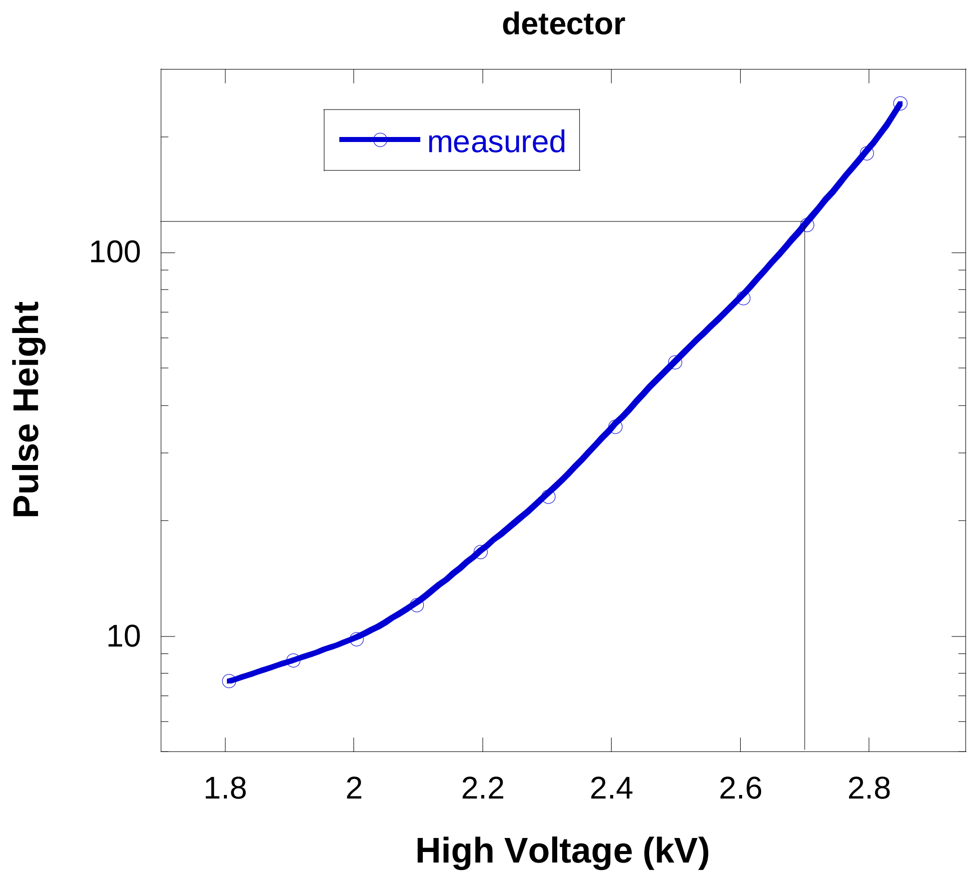

Figure 3: Variation of the gas multiplication factor with high voltage.

Amplifier Gain and Threshold

The detection electronics chain comprises a preamplifier then an amplifier for each cathode. The preamplifier plays the role of impedance matching mostly. The amplifier gain and lower level discrimination (LLD) settings must produce "healthy" amplified analog signals around 1 V in height.

Gain adjustments on the cathode amplifiers are made using a square wave signal (20 mV amplitude) injected into the anode plane and equalizing the output signals from the various cathodes. Final adjustments are made for the normal operation condition using a uniform scatterer such as (1 mm thick) plexiglass or water characterized by mostly incoherent (Q-independent) scattering.

Setting of the LLD also called "threshold" is described here for the CERCA detector. At the chosen high voltage setting of 2700 V, the LLD value is estimated by measuring the total detection count rate on the cathodes for increasing values of the LLD as shown in a figure. At low LLD settings, the electronics system is paralyzed by the processing of low amplitude noise, while at high LLD values, the count rate decreases due to the loss of neutrons detection events; this gives a reliable operating LLD around 275 mV.

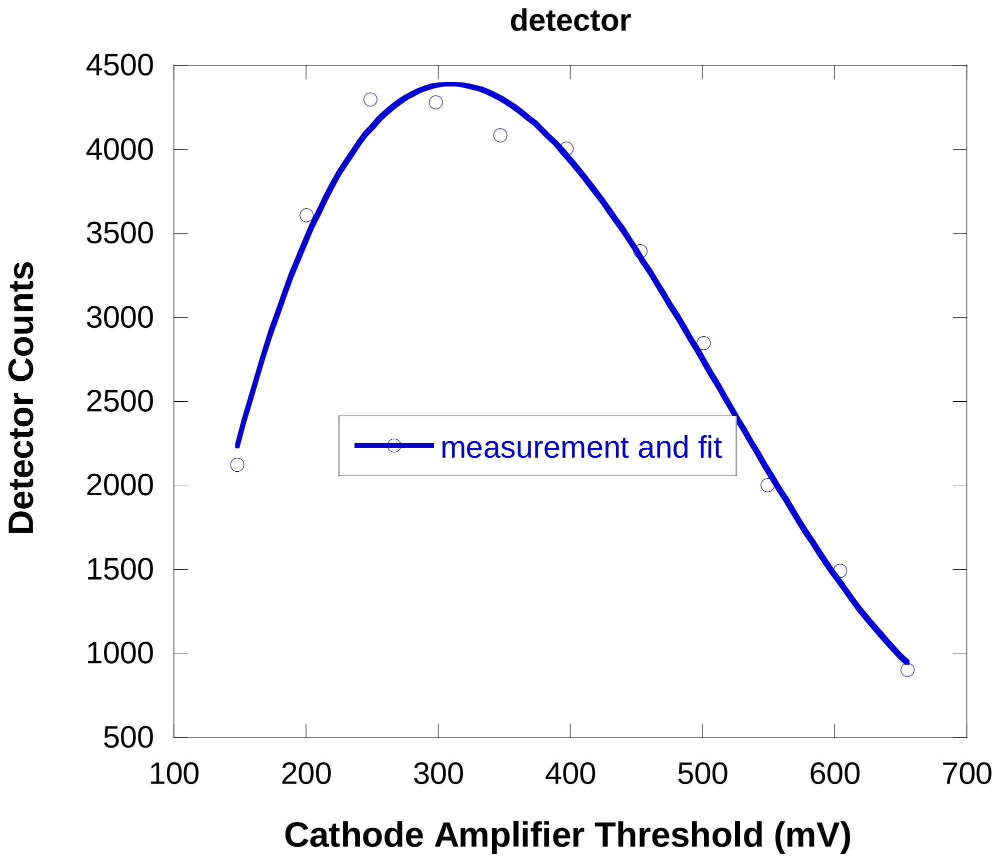

Figure 4: Setting of the cathode amplifier LLD (threshold) level. Optimal level is around the peak.

The Detector Proportional Region

Neutron detectors are "proportional" counters because the total amount of charge created remains proportional to the amount of charge liberated in the original neutron detection event. The neutron detector proportional counting region is mapped out by monitoring increases in detector count rate for increasing high voltage. A convenient operating high voltage is chosen in the proportional region and well below the "plateau" region as shown in a figure for a CERCA detector.

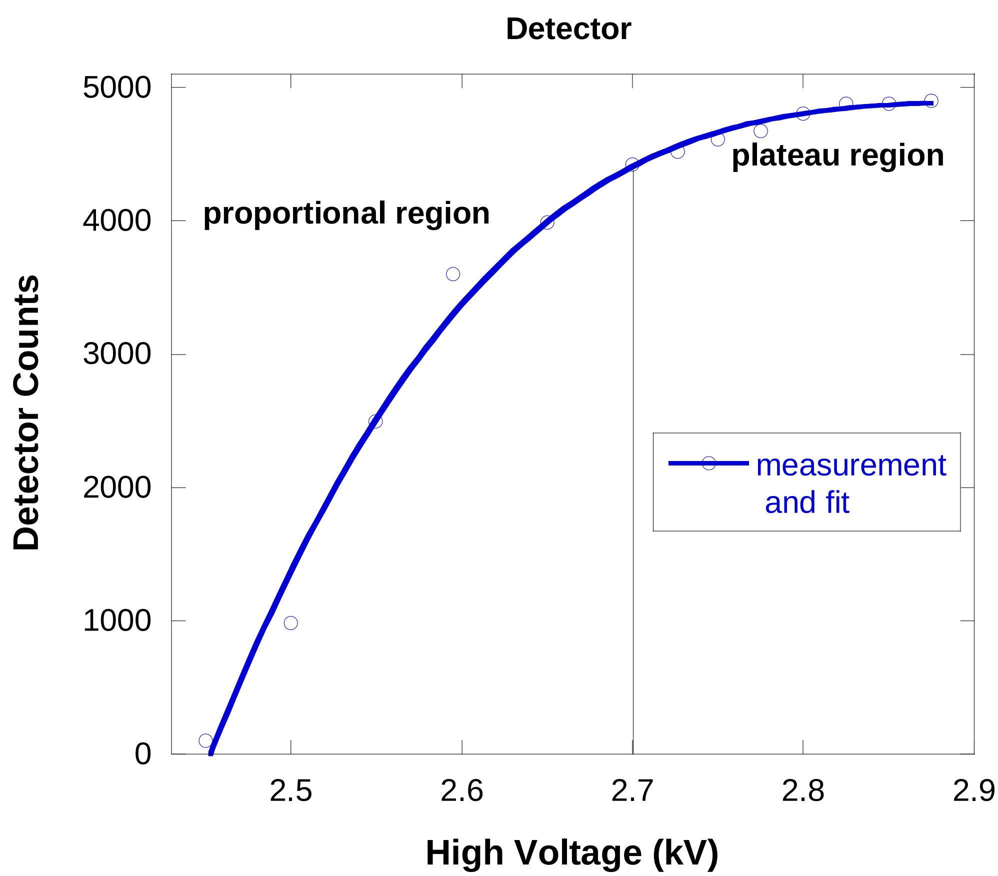

Figure 5: Determination of a convenient operating high voltage in the proportional region.

Spatial Resolution

Position sensitive detectors are characterized by their spatial resolution. The spatial resolution for a CERCA detector is determined as follows. Using a narrow (1 mm*2.54 cm) vertical slit to define a neutron beam, a scan of the detector response along the X cathodes is made by recording the count rates of individual cathodes when the detector is moved stepwise perpendicular to the neutron beam. Counts for two adjacent cathodes are shown in a figure. The detector spatial resolution is confirmed to be 1 cm and the counting efficiency is seen to remain reasonably constant within each detection band. This is seen by summing up counts for the two adjacent cathodes.

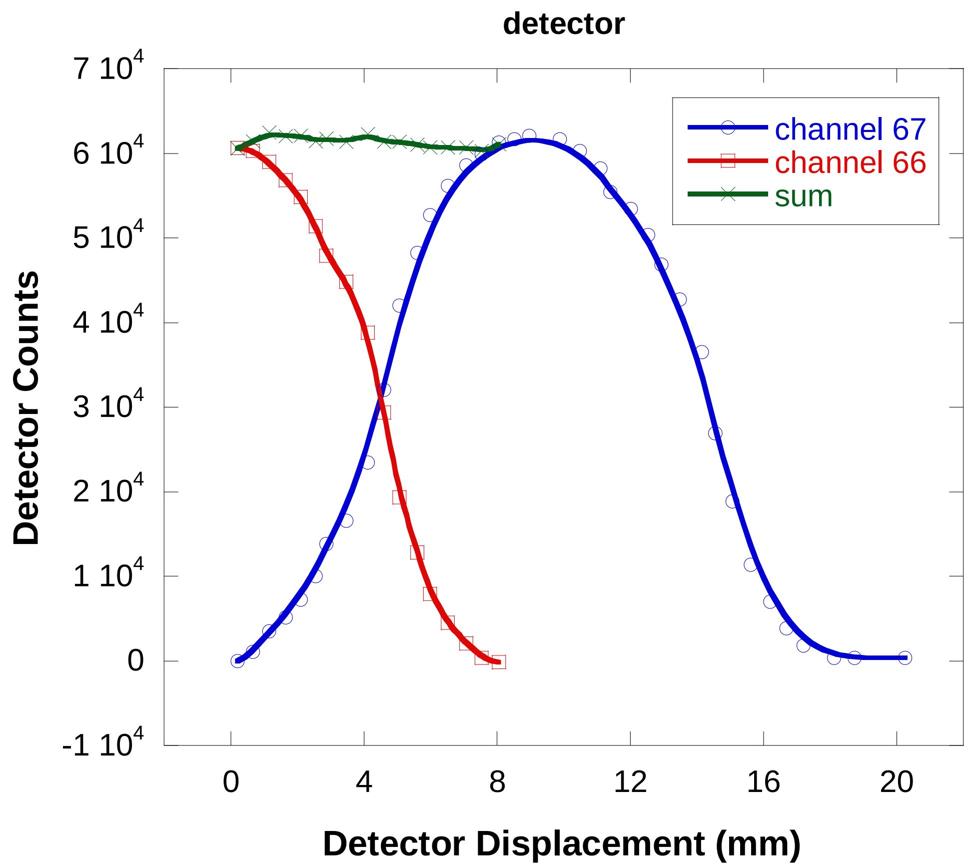

Figure 6: Determination of the detector spatial resolution.

Detector Efficiency

The detector absolute efficiency is measured using another (pencil) detector of known efficiency. The high gas pressure in the pencil detector gives it a very high efficiency at all wavelengths making it nearly "black". The detector efficiency was measured for an ORDELA detector and shown here. The ^{3}He neutron absorption cross section increases with wavelength ("1/v" absorber). This combined with various losses gives the observed variation.

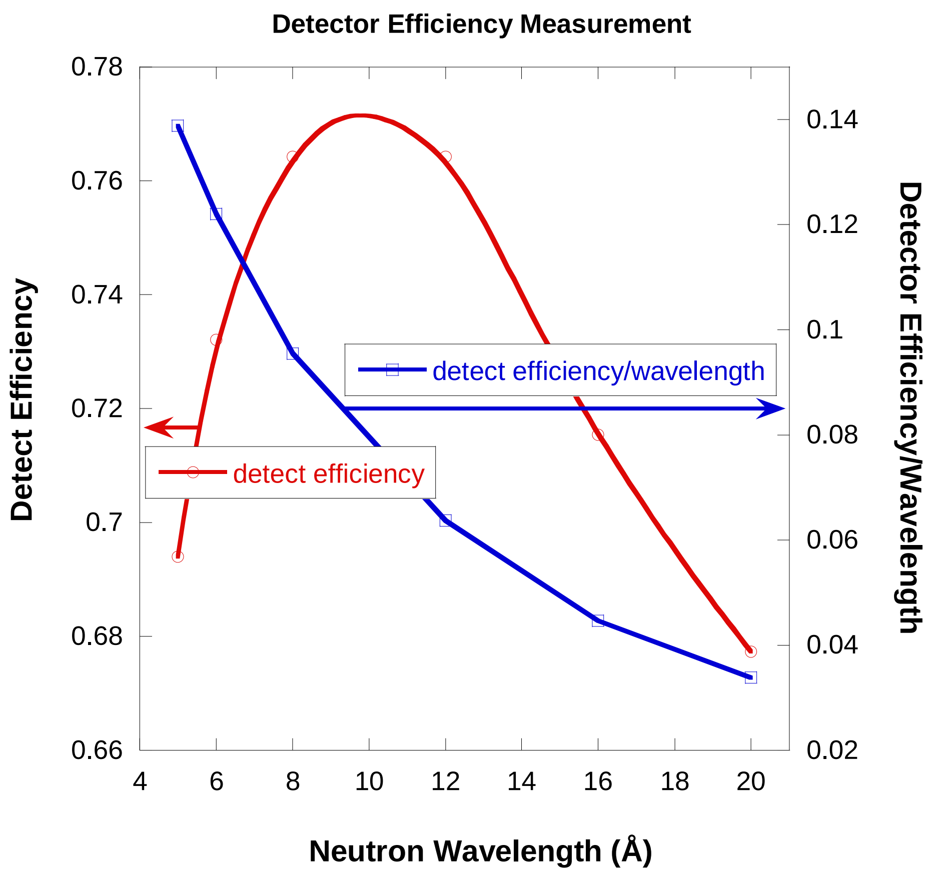

Figure 7: Variation of the detector efficiency (left axis) with increasing wavelength. Performing the "1/v" absorber correction involves dividing by the neutron wavelength (right axis).

Estimation of Dead Time

Dead time is inherent in most detection systems. Defining the "true" count rate as N_T, the "measured" count rate as N_M and the detection rate time constant as τ, the following argument is made. The fraction of total time for which the detector is dead is $N_T\tau$, and the rate at which true events are lost is $N_M N_T \tau$. That rate of loss is also given by N_T-N_M so that:

$$N_T - N_M = N_M N_T \tau \qquad (2)$$

This assumes "nonparalysable" systems whereby the detection system does not get paralysed by detected events. It keeps counting during signal processing. The true count rate is therefore estimated as:

$$N_T = \frac{N_M}{1 - N_M \tau}. \qquad (3)$$

Consider two measurements made with two different source apertures. These correspond to N_{T1} and N_{T2} and N_{M1} and N_{M2}. The ratio $R_T = N_{T1}/N_{T2}$ can be expressed in terms of the ratio $R_M = N_{M1}/N_{M2}$ as follows.

$$R_T = R_M \frac{1 - N_{M2}\tau}{1 - N_{M1}\tau}. \tag{4}$$

Or:

$$R_M = R_T + \tau N_{M1}(1-R_T). \tag{5}$$

Plotting R_M *vs* N_{M1} yields a linear behavior with intercept R_T and slope $m = \tau(1-R_T)$. The dead time τ can therefore be obtained from $\tau = m/(1-R_T)$.

In order to implement this procedure, the following measurement method is followed for an ORDELA detector. Two beam defining (sample) apertures of 1.27 cm and 2.27 cm diameters are used in turn. The neutron current crossing each of them is measured for different attenuation conditions. Different thickness plexiglass pieces are used to attenuate the neutron beam. The neutron currents are measured as count rates on the detector. An isotropic scatterer (thick piece of plexiglass) is used to "diffuse" the neutron beam therefore broadening the neutron spot on the detector. Plotting the ratio of the count rates for the two apertures with increasing count rate (for the 1.27 cm aperture) yields a linear behavior as shown in a figure. The intercept R_T is of course close to the ratio of aperture areas $R_T = (1.27/2.27)^2 = 0.313$ and the slope is around $m = 3.535*10^{-6}$ sec giving an estimated dead time of $\tau = m/(1-R_T) = 5.16$ μsec. This is the dead time for the entire detection system comprising the detector, the detection electronics chain and data acquisition system.

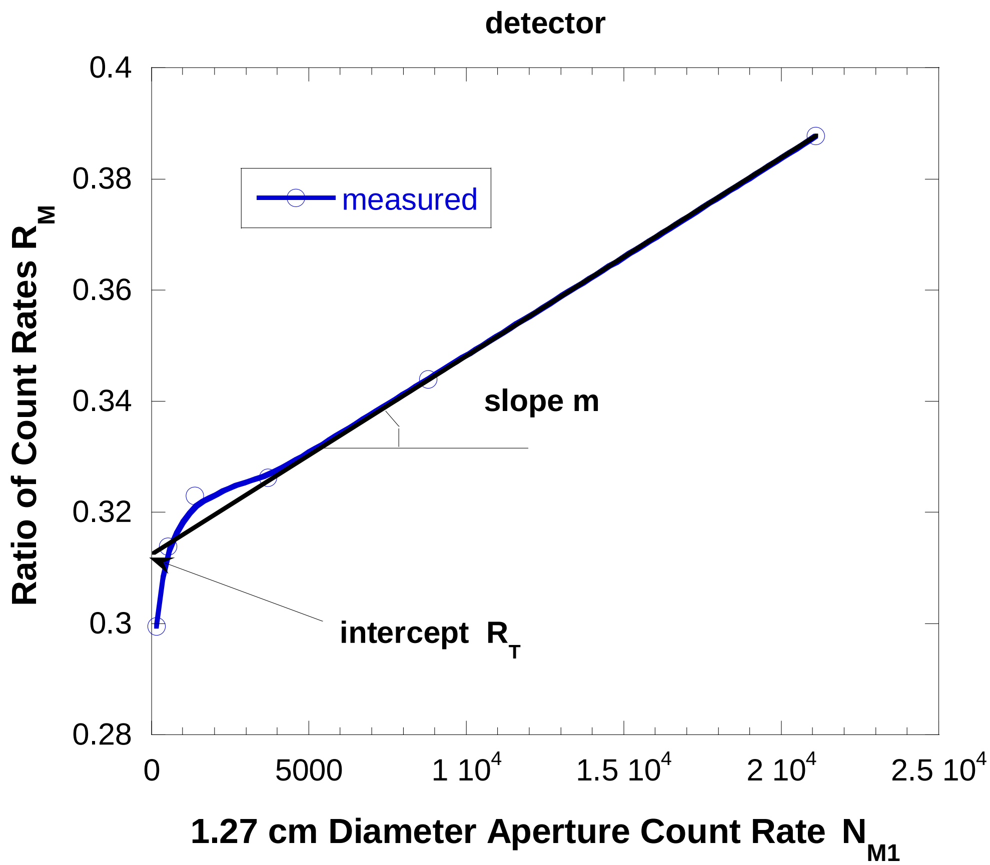

Figure 7: The dead time is estimated as $\tau = m/(1-R_T)$ where m is the slope and R_T is the intercept on the linear part of the measured curve.

Using the estimated dead time of $\tau = 5.16$ μsec, detector losses can be estimated when count rates are increased. The relative (percent) loss factor is given by:

$$L = \frac{N_T - N_M}{N_T} = \frac{N_T \tau}{1 + N_T \tau} \qquad (6)$$

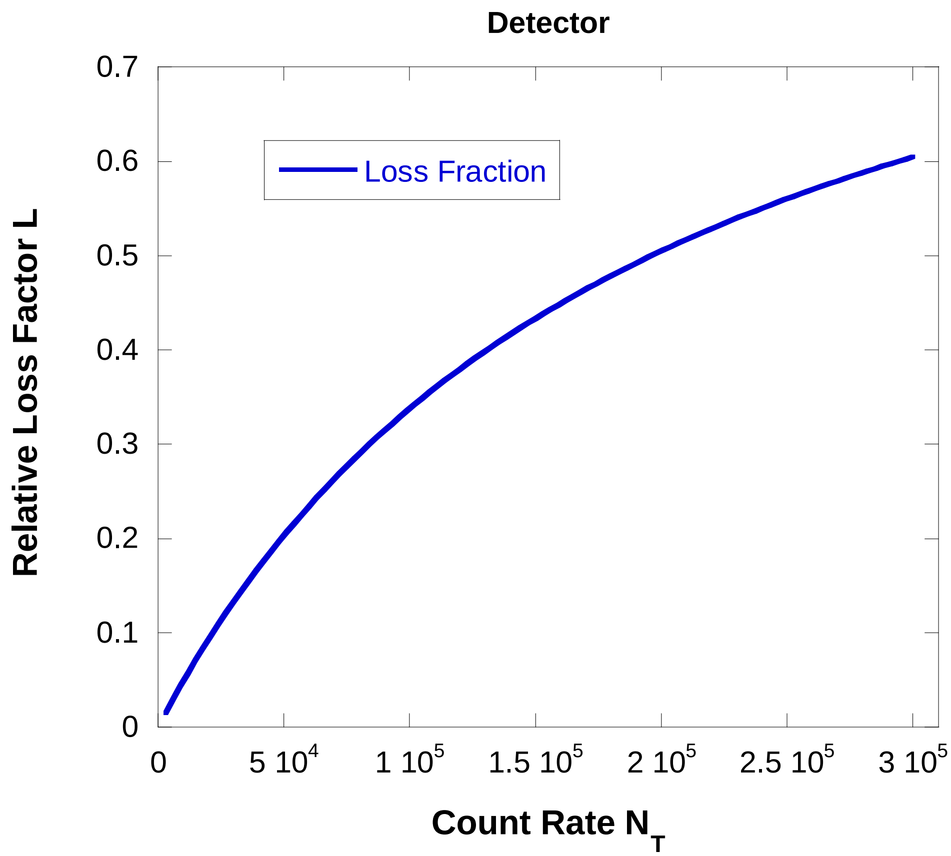

Figure 8: Percent loss factor as a function of count rate for a dead time of 5.16 μsec.

Table 1 gives estimates of dead time losses for increasing count rate.

Table 1: Estimation of dead time losses.

Count Rate N_T (counts per second)	Percent Loss Factor $L = (N_T - N_M)/N_T$
10,000 cps	4.85 %
30,000 cps	13.3 %
60,000 cps	23.4 %
90,000 cps	31.5 %

Detector Reliability

Using an intense localized neutron beam (> 10,000 cps), close inspection of the full 2D detector image shows whether miscoding "ghost" features are observed. These appear as faint spot "shadows" of the main neutron spot. Such shadows have been observed for both types of detector systems but are less severe in the ORDELA system. They are however not a problem since neutron area detectors usually operate in a less harsh neutron current condition.

4. OTHER NEUTRON DETECTORS

There are many types of other neutron detectors. Old type Boron (BF_3) neutron detectors are hardly ever used anymore due to safety considerations (the BF_3 gas is highly toxic). They have been replaced by He-3 detectors. Neutron scintillators use a conversion plate made of a neutron absorbing material (mostly Gd_2O_3) that emits gammas upon neutron absorption. The gamma rays are then detected as any other photons would through the use of photomultipliers. Neutron scintillators are very sensitive to gamma ray background.

Fission chambers are used as neutron beam monitors. They use a thin plate of fissile material (mostly ^{235}U) that releases two highly energetic fission fragments upon fission reaction with a total kinetic energy of 2 MeV. Fission chambers have very low efficiency (of order 10^{-4}) but large signal to noise ratios due to the high degree of ionization generated in the gas.

Note that the absorption cross section in neutron detectors varies inversely with neutron speed (1/v absorber) or linearly with neutron wavelength $\sigma_a(\lambda)$. Assuming a flat detection volume of thickness d and an atomic density ρ (number of absorbing atoms per cm^3), the detector efficiency is estimated as 1-T where T is the transmission through the detection volume and is given as $T = \exp[-\rho.\sigma_a(\lambda).d]$.

Table 2: Comparing a few characteristics for three types of neutron detectors. The B-10 and the He-3 types are proportional counters. The Li-6 type is a scintillator.

Detector Type	B-10(n,α)Li-7	He-3(n,p)T-3	Li-6(n,α)T-3
Energy of Reaction	2.79 MeV	0.76 MeV	4.78 MeV
Charged Particles Energies	α = 1.77 MeV Li = 1.01 MeV	p = 0.57 MeV T = 0.19 MeV	T = 2.73 MeV α = 2.05 MeV
Particles Range	α = 3 mm Li = 2 mm	p = 30 mm T = 6 mm	T = 0.04 mm α = 0.007 mm
Emitted Gammas	0.48 MeV	None	None
Typical Thickness	5 mm	20 mm	2 mm

Atomic Density	$0.053*10^{20}$ cm^{-3}	$0.81*10^{20}$ cm^{-3}	$173*10^{20}$ cm^{-3}
Absorption Cross Section at 5 Å	10,67 Barn	14,83 Barn	2,62 Barn
Efficiency at 5 Å	3 %	80 %	100 %

REFERENCES

G. Knoll, “Radiation Detection and Measurement”, John Wiley & Sons Inc. (1979).

P. Convert and J.B. Forsyth, “Position Sensitive Detection of Thermal Neutrons”, Academic Press (1983).

L.H. Schwartz and J.B. Cohen, “Diffraction from Materials”. Springer Verlag (1987).

G Marx, B. Hammouda, N. Thillosen, J. Jacobe, J.G. Barker and C. Glinka, “An ILL_Type Area Detector for SANS”, private communication (1993).

QUESTIONS

1. What are the two main gases used to detect neutrons? Which one is the most used nowadays?
2. Why is ^{3}He referred to as a “1/v” absorber?
3. What is the pulse height spectrum of a detector? How is it measured?
4. What is the “wall effect” feature in a pulse height spectrum? What is the “neutron peak”?
5. How does the coincidence method of detection work?
6. What is a fission chamber? How does it operate? What is it used for?
7. What are the two typical sizes of neutron area detectors used on SANS instruments? What is the typical detector spatial resolution?
8. Name four measurement tests for characterizing neutron area detectors?
9. How is the proportional detection region test performed? How is the multiplication gain factor test performed?
10. What is the gas multiplication factor?
11. How is the detector and electronics dead time test performed?
12. How is the spatial resolution test performed for neutron area detectors?
13. How to choose an operational threshold setting for an amplifier?
14. What is the percent loss for a non-paralysable detector system with 5.16 μsec dead time and 10,000 cps neutron current?
15. What are the two major suppliers of neutron area detectors for SANS instruments?
16. Find out a possible supplier of multi-channel analyzers (MCAs)?

ANSWERS

1. Neutron detectors use either BF_4 or ^3He. BF_4 is no longer used because if is highly toxic.
2. ^3He is referred to as a "1/v" absorber because its absorption cross section varies like 1/v (v being the neutron velocity or speed). This absorption cross section increases with neutron wavelength.
3. The pulse height spectrum of a detector is the distribution of electronics signal amplitudes outputted by the detector electronics. It is measured using a multi-channel analyzer (MCA).
4. The wall effect represents nuclear reaction products (either proton or triton) hitting the detector wall. The neutron peak corresponds to both reaction products being entirely absorbed in the gas (no wall effect).
5. The coincidence method registers a real detected event when an X and a Y cathode signals arrive in coincidence (i.e., within a specified time window).
6. A fission chamber is a very low efficiency neutron detector. It uses fissionable material (^{235}U mostly) to detect neutrons. An energy of 2 MeV is released as kinetic energy for the fission fragments. Fission counters are used as neutron beam monitors.
7. Neutron area detectors used on SANS instruments are either 64 cm*64 cm or 1 m*1 m in area. The spatial resolution is either 1 cm* 1 cm or 0.5 cm*0.5 cm.
8. The various tests performed to characterize neutron area detectors are: pulse height spectrum, multiplication factor, amplifier gain and threshold settings, gas proportional region, spatial resolution, detector efficiency, detector and electronics dead time.
9. The gas proportional region is determined by increasing the HV and recording the number of detector counts (see Figure 5).
10. The gas multiplication factor represents the number of electrons released from the absorption of one neutron.
11. The dead time is measured using two different apertures and varying the count rate each time by inserting attenuators in the beam. The dead time is given by $\tau = m/(1-R_T)$ where m is the slope and R_T the intercept of the ratio of counts (for the two apertures) *vs* count rate.
12. The spatial resolution test is performed by stepping the area detector laterally (perpendicular) to a neutron beam defined through a thin vertical slit.
13. The threshold (also called lower level discriminator or LLD) level for an amplifier is chosen as that setting that gives the maximum number of neutron counts.
14. Eq (6) gives the formula and Table 1 gives the answer of L = 4.85 % loss for a dead time of 5.16 μsec and 10,000 cps neutron current.
15. The two major suppliers of area detectors for SANS instruments are CERCA (Grenoble, France) and ORDELA (Oak Ridge, Tennessee, USA).
16. The company Canberra is a possible supplier of MCAs. A Google search with "multi channel analyzer suppliers" comes up with dozens of other possible suppliers.